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Using Non-Constant Failure Rates of Converters

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Reliability and Risk Assessment in a Power Electronic based Power System (PEPS): Using Non-Constant Failure Rates of Converters

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Keywords

«Reliability», «Power management», «Thermal stress», «Mission profile»

Abstract

In this paper, conventional power system reliability and risk indices are employed to evaluate the reliability of a Power Electronic based Power System (PEPS) employing Physics of Failure (PoF) based reliability functions. Mission profile based methods have presented to estimate the failure probability of converters which implies non-constant failure rates for converters during operating period. Hence, a piece-wise solution is proposed to employ the Markov Chain approach in order to evaluate the system level reliability of the PEPS with the non-constant failure rates. Furthermore, the impact of power management and thermal sharing on the system level reliability are studied. Numerical analyses and experiments are provided validating the proposed approaches.

Introduction

Power electronic converters play a main role in the energy conversion process of sources and loads in the future power systems. However, the power converters are exposed to new challenges in terms of reliability due to the most fragile components, i.e., power switches and capacitors. Based on the Physics of Failure (PoF) reliability analysis, these components are affected by the thermal cycling and temperature due to the different operation conditions [1]–[8]. So far, two major efforts have been carried out in order to improve the lifetime of the components. The first category is in charge of design procedure, where the converter parameters are designed based on the mission profile, which is known as Design for Reliability (DfR) [1]–[8]. The second approach introduces active thermal management for lifetime extension during operation of the converter in which the conditions are different from that of for DfR [2]–[10].

From the power system planning and operation point of view, reliability is classified into two categories: a) security – the ability of power system to respond to the disturbances – and b) adequacy – the ability of the system to supply the demand statically. In terms of adequacy of power system, generation capacity must be higher than the expected demand of system. One approach in designing and planning of generation system is to consider a reserve margin based on peak load of the system as well as considering the loss of the largest generation unit. However, these indices are insensitive to the failure rate and size of units. Hence, an aggregated model for loss of different capacity based on Markov approach has been presented and the risk of loss of load during a period is calculated [11]. Thereby, the indicators of Loss Of Load Expectation (LOLE), Loss Of Energy Expectation (LOEE) and Energy Index of Reliability (EIR) are introduced in order to evaluate the reliability and risk of system [11], [12].

In the last decade, the reliability analysis and improvement in power electronic converters have been widely addressed [1]–[10]. However, moving towards to the Power Electronic based Power Systems (PEPSs) makes it necessary to assess the impact of the lifetime of the converters on the power system reliability and risk for optimal planning and management of power systems. Thereby, including DfR [1]–[8] as well as reliability improvement by active thermal management in power converters and PEPSs [2]–[10], [13] are of significant importance.

Notably, active thermal control approaches have been presented in single or paralleled power converters in order to improve the lifetime and reliability of power switches [2]–[10]. Some approaches just control the heat, and hence, the average temperature of switches [2], [6], [10], whereas some techniques take into account the lifetime model based on PoF of switches [3]–[5], [7], [8]. For instance, decreasing thermal loss by different modulation strategies [2], [6], thermal management by active and reactive power control in a wind converter [3]–[5], reducing the thermal cycling by adapting the switching frequency [7], equalizing the junction mean temperature by modifying the loading of converters [10], and equalizing switch thermal damage [13] are some of the presented strategies in terms of active thermal management.

This paper focuses on the adequacy of the generation system in PEPSs where the main part of the generation system includes power converters as a vulnerable equipment in the system. Thereby, the effect of failure rate of power converters on the system reliability is investigated taking into account the PoF of converter components. In the following, concept of reliability in power systems is explained and the methodology of the reliability estimation in PEPSs is presented. Finally numerical analysis and outcomes are reported. Furthermore, an application case study with an experiment is also provided to show the impact of power management system on the thermal stresses and system level reliability indices.

Reliability model

Analysis of the reliability of the power system as a very large and complicated system is impossible even using super-computers. Hence, Billinton suggested hierarchically dividing the power system into three levels of generation systems, composite generations and transmission systems, and distribution systems [12]. Hierarchical Level I (HLI) is in charge of generation system and models the generation capacity adequacy. Furthermore, LOLE is used to evaluate the system reliability and risk in HLI.

LOLE determines the number of hours/days during a certain period of expected capacity shortages, which means the energy consumption, cannot be supported due to the loss of generation units. As a risk index, LOLE can be calculated as $LOLE = \sum_{i=1}^{n} p_i t_i$ [12], in which p_i is the probability of loss of expected capacity and t_i is the duration of the loss of the capacity usually in days. LOLE is the most accepted risk index for managing the generation capacity requirements in the utility industry [14].

The probability of the generation system (p_i) can be calculated based on a Markov Chain considering the combination of capacity out of service of different units. For a PEPS with N units shown in Fig. 1, the different failure combinations of units can be represented in the state space as shown in Fig. 2. For each unit, the probability of up state is A and the probability of down state is U, the probability of the system states are summarized in a Capacity Outage Probability Table (COPT) like Table III. The up/down state probability, also called availability/unavailability can be calculated as $A = \frac{\mu}{\mu + \lambda}$, $U = 1 - A$, where λ and μ are the failure (hazard) rate and repair rate of each unit, λ and μ are also called departure rate from each state. Furthermore, $\lambda = 1/MTTF$ (Mean Time To Failure) [12]. Table III presents the capacity outage probability which is formed based on Markov chain for the PEPS shown in Fig. 1, and the probability of different states are calculated based on the availability of each units. For example, for a state with M units up and (N-M) units down, the capacity outage probability can be found as:

$$p_i = \prod_{k=1}^{M} A_k \cdot \prod_{k=M+1}^{N} U_k \tag{1}$$

In order to simplify the COPT, the states with the same capacity outage can be combined to introduce a new state. Furthermore, the COPT should be incrementally sorted in terms of capacity out of service. The unsuccessful states include the states with the Capacity Out of Service (SOC) of higher than the Total Generation Capacity (TGC) mince system load (i.e, COS < TGC – P_{Load}) and the other states can supply the load.

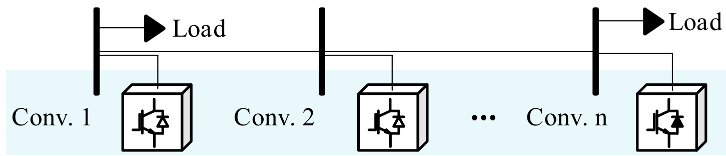

Fig. 1: A Typical Power Electronics based Power System (PEPS).

Table I: Capacity Outage Probability Table (COPT) for N-unit system

State	Capacity Out of Service (COS)	Unit outage combin.ation	COPT	State Probability
0	$S_0 = 0$	N units UP	All units UP	p_0
1	S_1	1 out of N units Down	1^{st} unit Down	p_1
2	S_2		2^{nd} unit Down	p_2
3	S_3		…	p_3
…	…	M out of N units UP	…	…
…	…		…	…
…	…		…	…
k-2	S_{k-2}	(N-1) units Down	$(N-1)^{th}$ unit UP	p_{k-2}
k-1	S_{k-1}		N^{th} unit UP	p_{k-1}
k	S_k ($k=2^N-1$)	N units Down	All Units Down	p_k

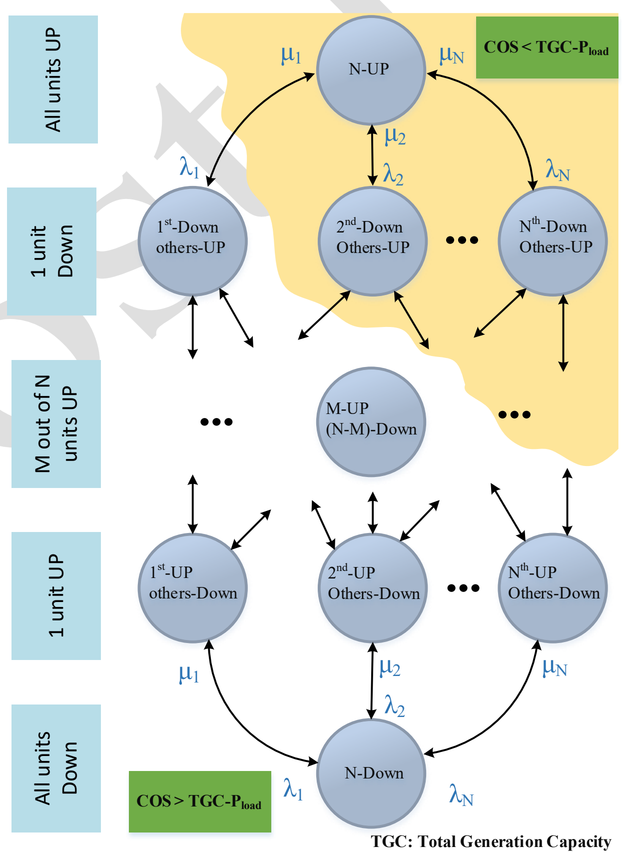

Fig. 2: State Space model of N generation unis.

In the traditional power system reliability assessment, λ and μ are the expected failure and expected repair rates, and hence, these values are considered to be constant during the lifetime of the unit. Thereby, Markov chain is employed to establish the reliability model of the system. However, at device level (i.e., power converters), the failure rate is not constant and the failure density function is based on Weibull distribution [15]. In order to calculate the reliability of a system with repairable components and applying Markov approach, the lifetime of converters should be considered to be constant during a short period [16]. In this paper, a piece-wise solution is utilized for evaluating the reliability of PEPSs, which is explained in the following.

Piece-wise solution

The failure density function of a converter $f(t)$ follows a Weibull distribution as:

$$f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \exp\left(-\left(t/\alpha\right)^{\beta}\right), \quad t \geq 0,\ \alpha > 0,\ \beta > 0 \tag{1}$$

where α is the scale parameter and β is the shape parameter. The shape and scale parameters can be defined by PoF analysis and Monte Carlo simulations [17]. The failure Cumulative Density Function (CDF) of a converter determines its unreliability. And the lifetime of a converter can be estimated by the unreliability function. For instance, $B\chi$ lifetime indicates that equipment has χ% probability to fail after the time or χ% population of a group of equipment will fail after this period [18].

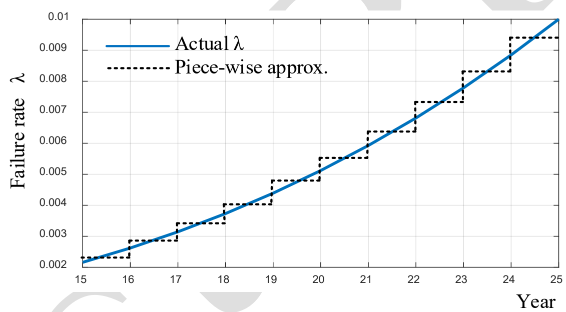

Fig. 3: Piece-wise approximation of a failure function.

Table II: Load model during one year.

Load Model	
Duration t (days)	Peak Load (kW)
28	30
31	50
120	38
102	42
62	35
22	60
Total 365	

The failure rate presented by a Weibull distribution is not constant unless in case of β =1. As already mentioned, in the traditional reliability assessment approaches, the expected value of the failure density function is chosen as $MTTF = 1/\lambda$. For example, for Weibull distribution, $MTTF = \alpha \cdot \Gamma(1+1/\beta)$. In the proposed approach, the B10 lifetime of a converter is divided into 1-year time slots and it is considered that the failure rate is constant in each time interval as shown in Fig. 3. By discretizing the failure rate, in each time slot, the failure distribution function is assumed to be exponential and hence the system behavior is lacking of memory. Thereby, the Markov approach can be employed to analyze the system reliability in each time interval [16]. The generation system adequacy can thus be calculated with a Markov approach like conventional methods employing constant failure rate during each time slot.

Reliability Calculation Results and Discussion

In this section, reliability of a PEPS with three converters shown in Fig. 4 is analyzed. The effect of non-constant failure rate on system reliability index, i.e., LOLE, is investigated and compared to the conventional approach. Moreover, an application case study with two converters are presented.

A. Numerical Analysis

For a three-unit PEPS shown in Fig. 5, different capacity outage states are represented in space state as shown in Fig. 5 and the corresponding COPT is summarized in Table III. Considering the load to be equal to, e.g., 32 kW, it cannot be supplied if the capacity outage is higher than (Total Generation Capacity – load = 70 – 32 = 38 *kW*). Following Table III, and Fig. 5, the states of 1, 2, 3, and 4 are the successful states and the states of 5, 6, 7, and 8 cannot supply the load, hence the probability of generation shortage at this load level is $p_4+p_5+p_6+p_7$. This probability is equal to the cumulative probability of capacity outage of 40 *kW* in Table III.

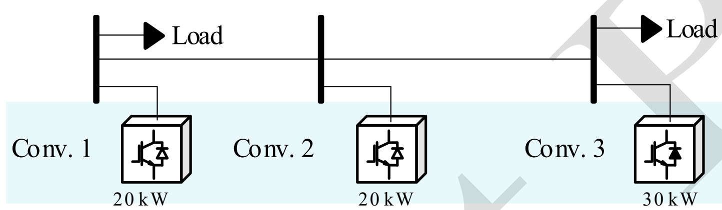

Fig. 4: A three-unit Power Electronics based Power System.

Table III: Capacity Outage Probability Table (COPT) for three-unit system.

Capacity Out of Service (COS)	COPT	State no.	Probability	Cumulative Probability
0 *kW*	AAA	1	p_0	$p_7+p_6+p_5+p_4+p_3+p_2+p_1+p_0=1$
20 *kW*	UAA/AUA	2, 3	p_1+p_2	$p_7+p_6+p_5+p_4+p_3+p_2+p_1$
30 *kW*	AAU	4	p_3	$p_7+p_6+p_5+p_4+p_3$
40 *kW*	UUA	5	p_4	$p_7+p_6+p_5+p_4$
50 *kW*	AUU/UAU	6, 7	p_5+p_6	$p_7+p_6+p_5$
70 *kW*	UUU	8	p_7	p_7

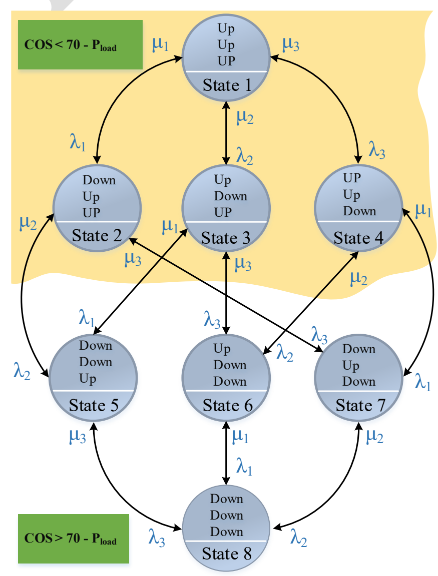

Fig. 5: State Space model of three generation unis.

In this section, five cases are considered with the given CDF of each converter in Fig. 6(a.1, b.1, c.1, d.1, and e.1). Furthermore, the peak load distribution during a year is given in Table II. In the presented case studies, different CDFs for converters are considered in case a, and the effect of increasing the failure rate of converter with shorter B10 lifetime is presented in case c. The effect of decreasing the failure rate of converter with longer B10 lifetime is also considered in case e. Case d illustrates the effectiveness of the piece-wise solution, where considering the exponential failure functions gives the same result of the conventional approach. Furthermore, case b presents that the conventional approach in some cases may be the worst-case design in terms of reliability. The LOLE calculation is only provided within the B10-lifetime of the converter with shorter B10 lifetime in each case, since after this period, the corresponding converter should be replaced with a new one and the system risk should be recalculated. The LOLE is calculated based on the conventional approach ($LOLE_{cnv}$) which gives fixed LOLE within the lifetime of the converter with shorter B10 lifetime as shown in Fig. 6(a.2, b.2, c.2, d.2, and e.2), with blue graphs. The LOLE results based on piece-wise approach ($LOLE_{pw}$) with 1-year time slots are also shown with red graphs in Fig. 6(a.2, b.2, c.2, d.2, and e.2).

Result 1: Following the results given in Fig. 6, the $LOLE_{cnv}$ is constant during the lifetime of converters and it is not affected by the failure rate of converters, while the piece-wise approach shows the effect of aging of converters on the LOLE. Therefore, any efforts for risk management based on the conventional approach in the early lifetime of the converters imposes unnecessary investments.

Result 2: Although the $LOLE_{cnv}$ introduces very high reliability in the early lifetime of converters, depending on the failure rate of converters, in the last years of lifetime of the converter with shorter B10 litetime, the LOLE may reach the conventional scheme as Fig. 6(b.1), or stay lower than it as shown in Fig. 6(a, c, d, and e). Case a shows the worst-case risk management by the conventional approach. However, in case c, the average value is higher than the actual value, i.e., $LOLE_{pw}$ implying the over-designed system in terms of risk management. Hence, the higher reliability is obtained by spending higher cost, which is not an optimal solution for power system planning and management.

Result 3: Comparing case a and c in Fig. 6(a, c), increasing the failure rate of the converter with shorter B10 lifetime (i.e., converter 3), will increase the LOLE. For instance, the $LOLE_{pw}$ in the 13th year, decreases from 0.592 to 0.265, whereas the $LOLE_{cnv}$ is changed from 1.257 to 1.13, which is almost negligible. Therefore, the proposed approach can properly illustrate the effect of failure rate of the converter with shorter B10 lifetime on the system reliability, while the conventional approach cannot sense it. Furthermore, comparing the results shown in Fig. 6(a, e), increasing the lifetime of the converter with longer B10 lifetime, and hence decreasing its failure rate, decreases the LOLE. Meanwhile, the change in the LOLE is very small, for instant, at 13th year, the $LOLE_{pw}$ is reduced from 0.265 to 0.253, and $LOLE_{cnv}$ is changed form 1.13 to 1.099.

As a result, the converter with shorter B10 lifetime has more effect on the system reliability and risk in comparison to the converter with longer B10 lifetime following the last two cases. Thereby, from the power system planning point of view, the converters with shorter B10 lifetime have more effect on the reliability and they are needed to be taken into account in the system risk management.

Result 4: Moreover, following result 3, decreasing the failure rate of one converter, will decrease the LOLE, hence any efforts in terms of the operation of the converters which reduces the corresponding failure rate, for example changing the loading of converters, will enhance the overall system reliability and decreases the system risk, e.g., LOLE.

Result 5: In Fig. 6(d.1 and d.2), a constant failure rates for converters are considered, and the same LOLE is obtained by both conventional and piece-wise approach. Hence, this validates the piece-wise approach for reliability assessment. Furthermore, following the results shown in Fig. 6, the $LOLE_{pw} \leq LOLE_{cnv}$, the conventional approach considers the extreme condition and hence any planning efforts performed based on the conventional method results in a high reliable system. However, in each system, there is an optimal reliable point where the cost of the system is minimized. Hence, even though the reliability assessment based on expected value of the failure density function as the reciprocal of λ (i.e., conventional approach) is acceptable, the risk management based on this method is not economical.

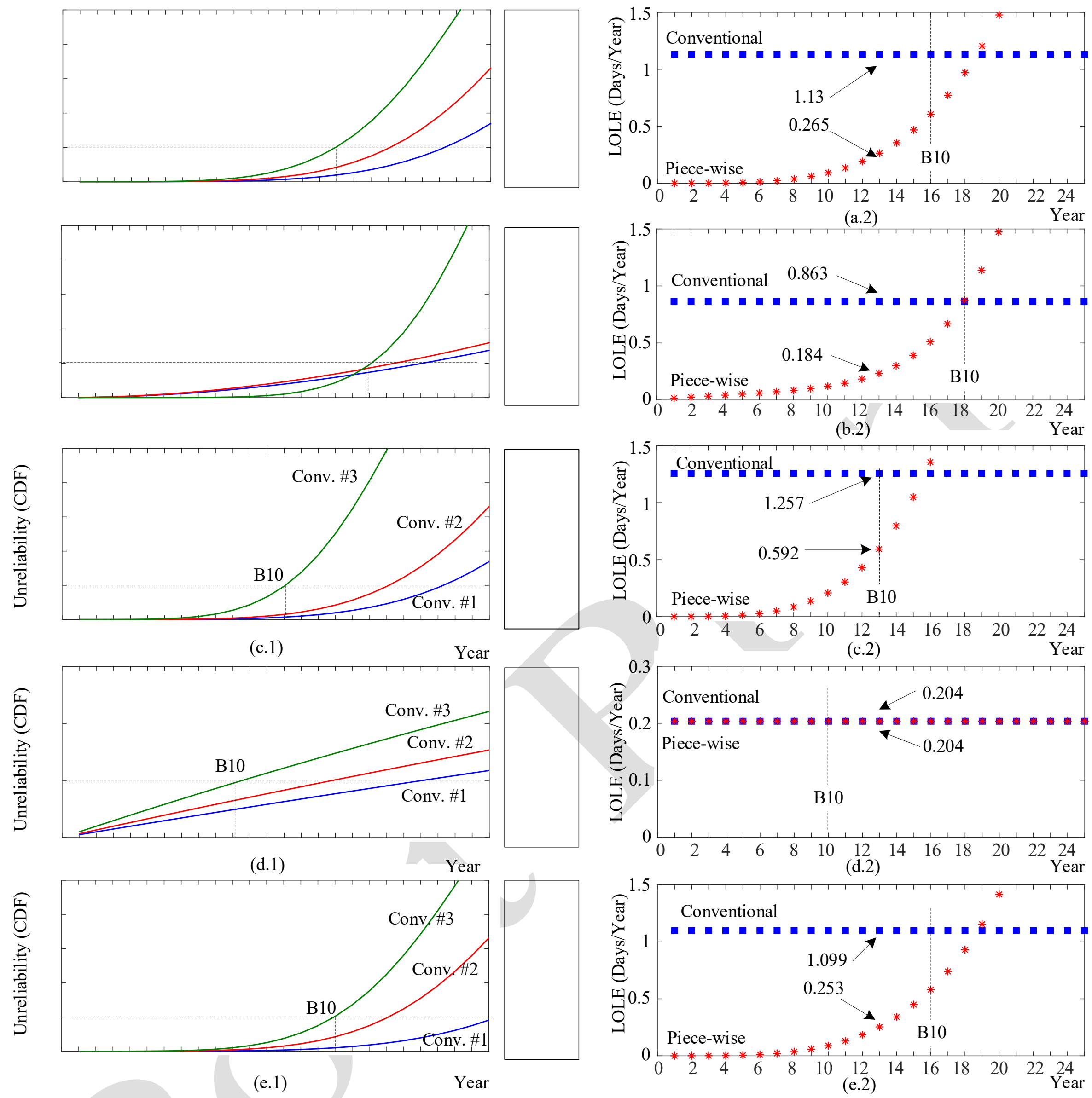

Fig. 6: Numerical analysis with Weibull distribution function (a, b, c, and e), and Exponential distribution function(d) – (a) main case for comparison, (b) worst-case design, (c) effect of increasing failure rate of converter with shorter B10 lifetime compared to case a, (d) constant failure rate, (e) effect of decreasing the failure rate of converter with longer B10 lifetime. (Note: μ is considered to be 16 repair/year for converters.)

B. Application Case Study

One of the main gains of the numerical system-level reliability assessment in a PEPS is highlighting the effect of failure rate on the system LOLE following results 3 & 4, where decreasing the failure rate of converter with shorter B10 lifetime will decrease the LOLE. The failure rate of a converter depends on different parameters which finally affect the physics of devices. Furthermore, capacitors and active switches are the most vulnerable components of a converter [17]. For instance, following (3) the mean junction temperature (T_{jm}) and wsing (ΔT_j) reduces the active switches number-of-cycles-to-failure (N_f) and consequently the lifetime of the switches.

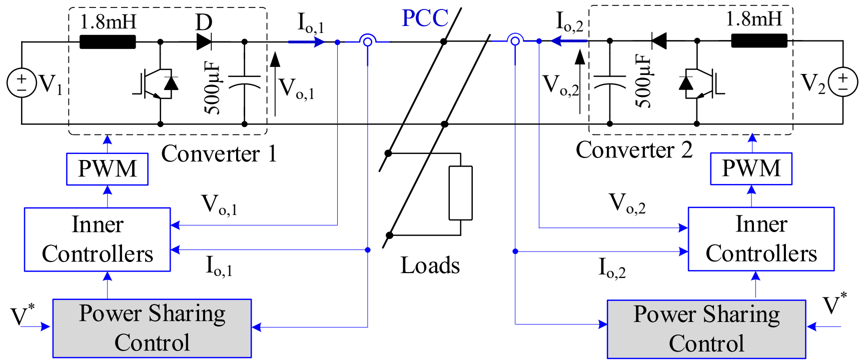

Fig. 7: The implemented dc PEPS with two dc/dc boost converter.

$$N_f = A \cdot \Delta T_j^{\alpha} \cdot exp\left(\frac{E_a}{k_b \cdot T_{jm}}\right) \tag{3}$$

The more stress on the switch of a converter, the more failure occurrence is expected. In order to decrease the stress of converters, modifying the loading of converters by the power management system according to the converter reliability will enhance the system reliability. For instance, in a simple dc PEPS with two dc-dc boost converters connected to a common load as shown in Fig. 7, the effect of load sharing between the converters are shown in Fig. 8. The load is periodically changed between 2.5 and 5 kW, each for 5 minutes and the temperature cycling on the heatsink of switches is measured. As shown in Fig. 8, by changing the loading of converters, the temperature swing is changed. Following (3), the same temperature swing on the switches results in the same lifetime consumptions, and hence, the same failure rates. As a result, the system level reliability index, LOLE, can be changed by modifying the failure rate.

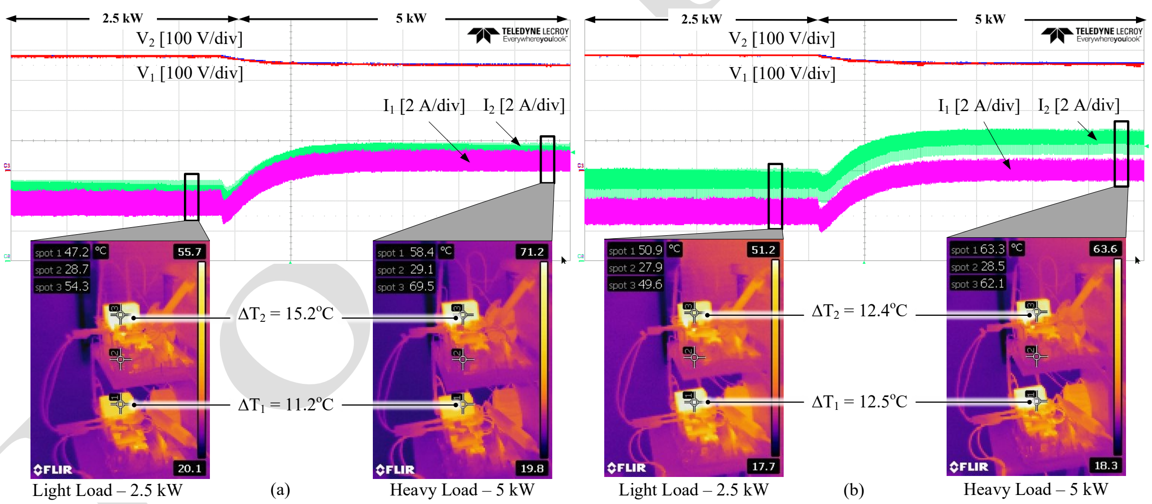

Fig. 8: Experimental validation of effect of loading of converters on the temperature swing: (a) equal, and (b) unequal load sharing.

In order to show the impact of load sharing on the LOLE of the dc PEPS, the reliability of the converters under an annual mission profile with a daily pattern given in Fig. 9 is estimated considering power sharing ratio (I_{o1}/I_{o2}) of 1 and 1.4 between the two dc/dc converters and demonstrated in Fig. 10. The failure CDF on the IGBT switches are predicted according to [17], and the thermal model of the IGBT switches are obtained from the datasheet of IGB10N60T from Infineon. For equal power sharing, the unreliability function of the converters are shown in Fig. 10(a.1) and the corresponding IGBT junction temperature is shown in Fig. 10(a.2). Moreover, the unreliability functions and the IGBT junction temperature for the power sharing ratio of 1.4 is depicted in Fig. 10(b.1 and b.2) respectively. As shown in Fig. 10(a.2 and b.2), Increasing the power sharing ratio, reduces the junction temperature swing of the first converter from 68.5 to 62.5°C, and the maximum temperature by 10°C. Furthermore, increasing the loading of the second converter will increase the temperature swing from 50.7 to 52.8°C and maximum temperature by 3°C. Consequently, the failure probability or the unreliably of the second converter will be decreased as shown in Fig. 10(a.1 and b.1). As a result, the LOLE of the system will be affected by the power sharing strategy as shown in Fig. 11 in which increasing the sharing ratio will reduce the LOLE, accordingly the risk of generation shortage will be reduced.

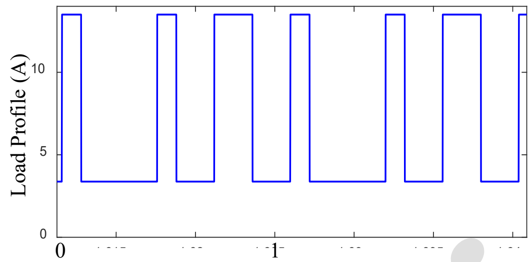

Fig. 9: daily load profile of the dc PEPS.

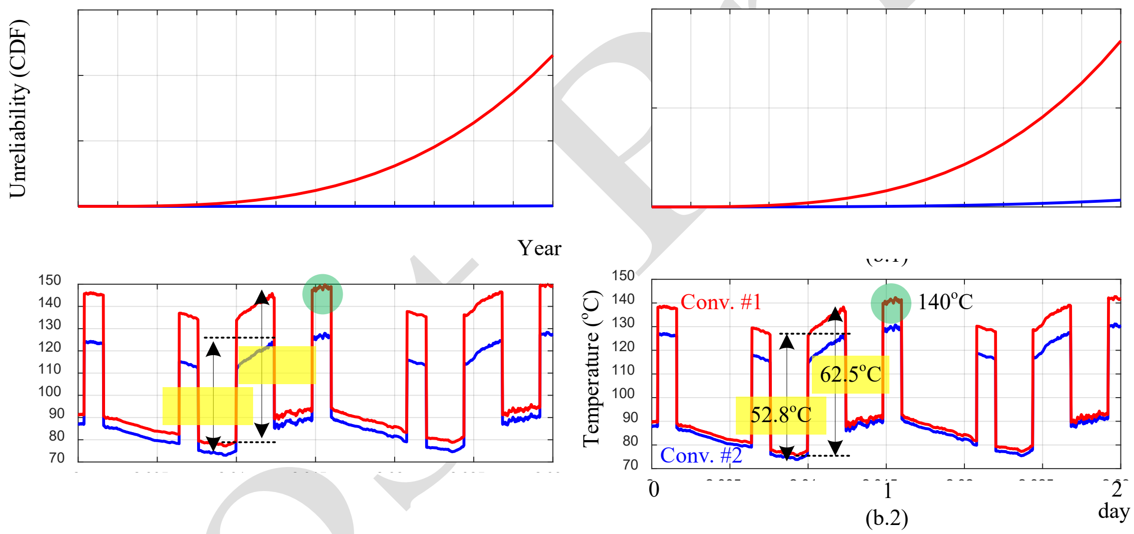

Fig. 10: Numerical analysis with two converters with equal and unequal power sharing ratio: (a.1) unreliability functions under equal sharing ratio, and (a.2) converters' IGBT junction temperatures, (a.2) unreliability functions with sharing ratio equal to 1.4 and (b.2) converters' IGBT junction temperatures.

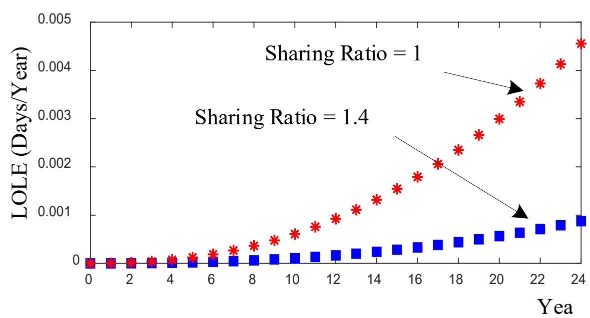

Fig. 11: LOLE estimation in the dc PEPS with two converters considering equal and unequal power sharing ratio. (Note: μ is considered to be 16 repair/year for converters.)

Conclusions

In this paper, the reliability of a PEPS is evaluated employing the conventional power system reliability and risk indices. The LOLE index is modified and adapted for the PEPSs by discretizing the non-constant failure rate of converters estimated according to the physics of failure of converter components. Thereafter, the Markov Chain approach is employed to calculate the reliability of the PEPS. As a result, the conventional power system assumption considering failure rate as the reciprocal of MTTF of each unit can not make sense for PEPSs with non-constant failure rates. The proposed approach shows that the conventional method considers the extreme conditions and in the most cases provides a high reliable system, while spending much costs and investments to achieve such high reliability. Moreover, an application case study is provided to illustrate the impact of power management on the thermal stress of the converter switches and hence their failure rates. As a result, the PEPS reliability and risk can be managed by the power management system. Numerical analyses and experiments validate the effectiveness of the proposed system level reliability estimation approach for PEPSs.

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